THE ASTROPHYSICAL JOURNAL, 162:837–839, December 1970

^{53}Mn AND THE AGE OF GALACTIC COSMIC RAYS

DONALD V. REAMES
NASA/Goddard Space Flight Center, Greenbelt, Maryland
Received 1970 May 11

ABSTRACT

A new measurement is suggested for obtaining information on the mean age of the galactic cosmic rays. The technique is based on a half-life of $\sim 2 \times 10^6$ years for ^{53}Mn which may be produced copiously below 200 MeV per nucleon by the fragmentation of cosmic-ray ^{56}Fe during its passage through interstellar or intergalactic hydrogen.

At present, our primary information on the mean age of the galactic cosmic radiation comes from the abundance of the light nuclei Li, Be, and B which are believed to have been produced by fragmentation of heavier nuclei during their passage through interstellar space (Ginzburg and Syrovatskii 1964; Meyer 1969). These abundances imply that the radiation has traversed ~ 4 g cm^{-2} of interstellar material, but owing to variations in the density of that material, the mean age of the cosmic rays inferred can range from 10^6 years for confinement of the radiation to the galactic disk to 10^9 years for confinement to the halo. An age which is larger yet would presumably apply to cosmic rays of metagalactic origin.

Attempts have been made to infer the age of the radiation from the shape of the spectrum of cosmic-ray electrons (Ramaty and Lingenfelter 1966; Fanselow *et al.* 1969).

A more direct age determination could come from the observation of a long-lived radioactive nuclide in the cosmic rays, and ^{10}Be has been suggested (Hayakawa, Ito, and Terashima 1958) as a possible candidate. Unfortunately, however, recent measurements (Yiou *et al.* 1968; Yiou 1968) of the cross-section for production of ^{10}Be emphasize the difficulty of detecting this nuclide in the presence of the lighter Be isotopes (Shapiro and Silberberg 1968).

With improvements of experimental techniques it has become possible to examine the abundances of elements up to the vicinity of Fe, and it has been found that elements immediately below Fe are remarkably consistent with their having been produced by fragmentation of Fe itself during its passage through about 2 g cm^{-2} of interstellar hydrogen (Kristiansson 1966; von Rosenvinge, Webber, and Ormes 1969; Mathiesen *et al.* 1968).

This circumstance leads us to suggest the possibility of using the abundance of Mn, with its strong dependence on the production of the nuclide ^{53}Mn, with a half-life of 2×10^6 years, as an indicator of the age of cosmic-ray Fe.

Any discussion of a nuclide such as ^{53}Mn whose only mode of decay is by orbital-electron capture must be prefaced by a discussion of the cross-section for capture of free electrons into orbit at high velocity. Certainly a highly relativistic nucleus would be stripped of orbital electrons and thus prevented from decaying by this mode. This situation is qualitatively similar to that for ^{7}Be described by Lawrence and Levinger (1966).

Estimates of the cross-section for the radiative capture of electrons into orbit may be made from the well-understood inverse process, the relativistic photoelectric effect (Heitler 1954). Using these data and the principle of detailed balance, one finds a cross-section which falls below 1 barn at 230 MeV/nucleon and reaches 200 mb at 500 MeV/nucleon. In this region the cross-section therefore becomes small with respect to the cross-section for nuclear interaction. The cross-section for nonradiative capture of electrons into orbit may be estimated from the Brinkman-Kramers (1930) relation and is found to be almost two orders of magnitude smaller than the cross-section for radiative capture in this region, in contrast to the situation at low energies and charges where measurements of atomic cross-sections are made.

When we examine the cross-section for loss of an orbital electron, we find that the estimated (Bohr 1948) value is $\sigma_l \sim 200$ barns at an energy as high as 200 MeV/nucleon. At first sight this large cross-section would appear to preclude ^{53}Mn decay. However, when we consider the metagalactic or halo environment in which the "old" cosmic rays would propagate, where the particle density is $n \sim 10^{-3}$ atoms cm^{-3}, we find that the mean time between electron-removing collisions is $\tau = (n\sigma_l\, \beta\gamma c)^{-1} \approx 10^7$ years. Since this time is considerably larger than the ^{53}Mn half-life, capture of an electron into orbit leads to decay before the electron can be removed, as we shall see from the calculated results.

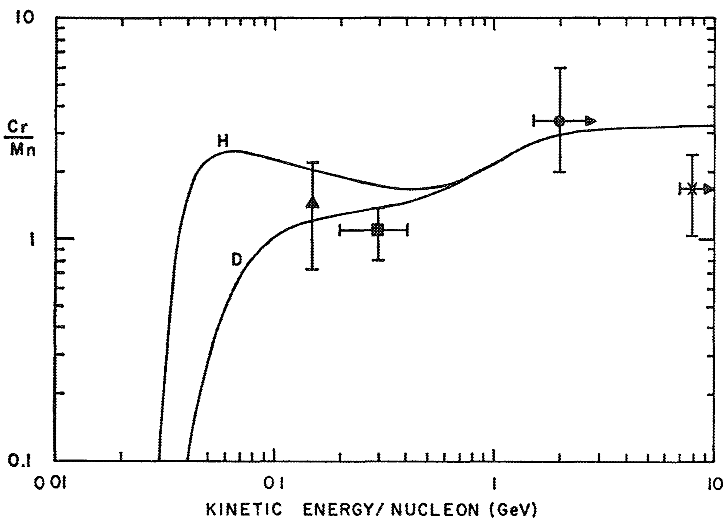

FIG. 1.—Ratio of Cr to Mn in the cosmic radiation. *Curves*, theoretically calculated ratio for the cases of galactic-disk containment (D), where ^{53}Mn survives, and halo containment (H), where it decays. Extragalactic propagation is indistinguishable from curve H. Data shown by the triangle, square, circle, and cross are from Garcia-Muñoz and Simpson (1969), Price *et al.* (1968), von Rosenvinge *et al.* (1969), and Mathiesen *et al.* (1968), respectively.

The Brinkman-Kramers cross-section for capture and the Bohr cross-section for loss agree to within 20 percent with the experimental results of Heckman, Hubbard, and Simon (1963) for ^{40}Ar in Zapon at 10 MeV/nucleon.

Cross-sections for the production of ^{53}Mn have been calculated by the Monte Carlo cascade-evaporation method of Bertini (1962); they also have been estimated by using the semiempirical relation of Rudstam (1966; Waddington 1969) at high energies. These cross-sections rise from $\sim$30 mb at high energies to a maximum of $\sim$300 mb at 50 MeV/nucleon. No direct measurements of the cross-section for ^{53}Mn production exist; such measurements in the 50–200-MeV region of interest are clearly needed.

The ratio of the fluxes of Cr and Mn shown in Figure 1 for the cases of galactic-disk and halo environments have been calculated by using the theoretical predictions of the cross-section. In the calculation of the ratios, equations similar to those described by Fichtel and Reames (1968) have been used to propagate the nuclei through 3 g cm^{-2} of hydrogen although the results are not sensitive to the amount of material traversed. Into these equations we have incorporated capture and loss cross-sections of the form

$$\sigma_c = 3.4 \times 10^4 E^{-2.1} \quad \text{and} \quad \sigma_l = 9.5 \times 10^5 E^{-1}\,,$$

where the energy per nucleon, E, is expressed in MeV and the cross-sections, σ, are in barns. Nuclei with and without electrons were treated as separate species, and those with electrons were allowed to decay with an effective cross-section

$$\sigma_\tau = (n\beta\gamma c\tau)^{-1} ,$$

where τ is the mean life of the decaying species and n is the density of the material traversed, taken as 1, 10^{-3}, and 10^{-5} atoms cm^{-3} for disk, halo, and intergalactic material, respectively. Also plotted in Figure 1 are measurements of this ratio for the galactic cosmic rays. Based on the existing cross-sections used, a young age associated with local origin and/or containment in the galactic disk seems to be most consistent with the available data; such a conclusion, however, must be regarded as highly tentative at present.

Finally, it should be noted that the results would be sensitive to the presence of Mn or Cr in the source. The abundances of these elements in the source are probably $\lesssim 10$ percent of Fe (Warner 1968; Bodansky, Clayton, and Fowler 1968). It may be possible to eliminate contributions from the source by observing the Cr/Mn ratio at high energies and by observing its energy dependence. The Cr/Mn ratio should be highly insensitive to effects dependent on the propagation model used, such as distributions in interstellar path length, insofar as their energy dependence is small in the 50–200 MeV/nucleon region.

While low-energy measurements of the iron-fragmentation cross-sections are clearly required (especially ^{56}Fe$(p,\alpha)^{53}$Mn), an estimate of the mean age of the cosmic radiation based on ^{53}Mn presently appears more readily accessible than one based on ^{10}Be whose production cross-section is known to be lower than that of its neighbors by an order of magnitude.

These considerations have recently been extended to other electron-capture nuclei by Roelof (1970).

REFERENCES

Bertini, H. W., 1962, *Monte Carlo Calculations on Intranuclear Cascades*, Oak Ridge National Laboratory Report ORNL-3383 (unpublished).

Bodansky, David, Clayton, Donald G., and Fowler, William A. 1968, *Phys. Rev. Letters*, **20**, 161.

Bohr, N. 1948, *Kongelige Danske Videnskabernes Selskab. Mat.-Fys. Medd.*, **18**, No. 8.

Brinkman, H. C., and Kramers, H. A. 1930, *K. Nederlands Akad. Wetenschappen*, **33**, 973.

Fanselow, J. L., Hartman, R. C., Hildebrand, R. H., and Meyer, Peter. 1969, *Ap. J.*, **158**, 771.

Fichtel, C. E., and Reames, D. V. 1968, *Phys. Rev.*, **175**, 1564.

Garcia-Muñoz, M , and Simpson, J. A 1969, *Proc. XI Int Conf. Cosmic Rays, Budapest* (to be published).

Ginzburg, V. L., and Syrovatskii, S. I. 1964, *The Origin of Galactic Cosmic Rays* (New York: Macmillan Company).

Hayakawa, S., Ito, K., and Terashima, Y. 1958, *Progr. Theoret. Phys. Suppl.*, **6**, 1.

Heckman, Harry H., Hubbard, Edward L., and Simon, William G. 1963, *Phys. Rev.*, **129**, 1240.

Heitler, W. 1954, *The Quantum Theory of Radiation* (Oxford: Clarendon Press).

Kristiansson, K. 1966, *Ark. F. Fys.*, **32**, 285.

Lawrence, C. E., and Levinger, J. S. 1966, Rensselaer Polytechnic Institute, preprint (unpublished).

Mathiesen, O., Long, C. E., Freier, P. S., and Waddington, C. J. 1968, *Canadian J. Phys.*, **46**, S583.

Meyer, Peter, 1969, *Ann Rev. Astr. and Ap.*, **7**, 1.

Price, P. B , Fleischer, R. L , Peterson, D D., O'Caellaigh, C , O'Sullivan, D , and Thompson, A 1968, *Phys. Rev Letters*, **21**, 630.

Ramaty, Reuven, and Lingenfelter, Richard E. 1966, *Phys. Rev Letters*, **17**, 1230.

Roelof, E. C. 1970, private communication.

Rosenvinge, T. T. von, Webber, W. R., and Ormes, J. F 1969, *Ap. and Space Sci.*, **5**, 342.

Rudstam, G. 1966, *Z. Naturforschung*, **21a**, 1027.

Shapiro, M. M., and Silberberg, R. 1968, *Canadian J. Phys.*, **46**, S561.

Waddington, C. J., 1969, *Ap. and Space Sci* , **5**, 3.

Warner, Brian. 1968, *M.N.R.A.S.*, **138**, 229.

Yiou, F. 1968, *Ann. Phys.*, **3**, 169.

Yiou, F., Baril, M., Dufaure de Citres, J., Fontes, P., Gradsztajn, E., and Bernas, R. 1968, *Phys. Rev.*, **166**, 968